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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Effects of variably layered coarse textured soils on plant available water and forest productivity

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Abstract

Reforestation is a primary end use for reconstructed soils following oil sands mining in northern Alberta, Canada. Limited soil water conditions in this climate will restrict plant growth. The objective of this study was to evaluate the effect of soil texture (gradation and layering) on plant available water and consequently on forest productivity for reclaimed coarse textured soils. A previously validated system dynamics (SD) model of soil water dynamics was coupled with ecophysiological and biogeochemical processes model, Biome-BGC-SD, to simulate forest dynamics for different soil profiles. These profiles included contrasting 50 cm textural layers of finer sand and coarser sand in which the sand layers had either a well graded or uniform soil texture. These were compared to homogeneous profiles of the same sands. Two tree species of jack pine (*Pinus banksiana Lamb)* and trembling aspen (*Populus tremuloides Michx.*) were simulated using a 60-year climatic data base from northern Alberta. Available water holding capacity (AWHC) was used to identify soil water regime, while leaf area index (LAI) and net primary production (NPP) were used as indices of forest productivity. Using the published and previously validated physiological parameters, the Biome-BGC-SD was used to study the responses of forest leaf area index and potential productivity to AWHC on different soil profiles. Simulated results indicated that layering of uniform fine sand overlying coarse sand could significantly increase AWHC in the 1-m profile for coarse textured soils. This enhanced AWHC could result in an increase in forest LAI and NPP. The extent of the increase varied with coarse sand gradation and vegetative types. The simulated results showed that the presence of 50 cm of uniform fine sand overlying 50 cm of graded coarse sand would provide an effective reclamation prescription to increase AWHC and forest productivity.

Keywords: plant available water; soil layering; forest productivity; boreal forest.

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1. Introduction

Reforestation is a primary end use for reconstructed soils following oil sands mining in northern Alberta, Canada. Approximately 20% of the final reclamation landscape in the oil sands region will be comprised of coarse textured soils. Coarse textured soils are generally low in available soil water and nutrients in which plant growth is strongly restricted. Previous research has shown that layering of sandy soils can enhance water availability for plant growth (Yang et al. 2004; Huang et al. 2011a); however, the influence of textural gradation on these enhancements is not well defined.

Because soil hydraulic properties are strongly related to particle size distribution, the difference in textural gradation can result in the differences in hydraulic properties (i.e., soil water retention curve (SWRC), hydraulic conductivity) of soils. Aubertin et al. (2003) studied the effect of textural gradation on the equivalent capillary rise in a soil above water table, and found that uniform soils always had a lower capillary rise than a graded soil of similar mean grain size.

Engineered soil covers are often designed to include a capillary barrier, a layering of a finer textured soil over a coarser textured soil (Stormont 1996). The presence of a capillary barrier can increase the available water holding capacity (AWHC)of the finer layer and in some cases maintain elevated levels of saturation which can restrict gas movement (Khire et al. 2000, Yang et al. 2004). The elevated water content of the finer textured soil is created by the low values of suction (negative water pressure) that develop within the coarser soil under even small rates of infiltration. At these low values of suction, the overlying finer textured soil layer is able to retain high values of water content, much greater than those expected at normal field capacity. The stored water in the finer textured layer is later removed by evaporation and transpiration, lateral drainage, or percolation (breakthrough into the lower layer) (Yang et al. 2004). Therefore, the capillary barrier increases the water available for plant growth. Although the use of capillary barriers is well developed within the engineering literature, there are no reports in which the combinations of layering and textural gradation are evaluated as to the influence they have on the effectiveness of the performance of a capillary barrier.

Currently, land capabilities for forest ecosystems on natural and reclaimed lands in the Athabasca oil sands region are subject to evaluation and classification by the Land Capability Classification System (LCCS) for Forest Ecosystems (CEMA 2006). The LCCS uses the AWHC to identify the soil water regime required for various ecosites. The AWHC is the volume of water stored within the rooting zone as represented by the difference in water content between field capacity (FC) and wilting point (WP). The AWHC is a measure of water availability in natural and reclaimed soil profiles, but it ignores the effects of soil layering, climatic variability, and plant water physiological properties (Huang et al. 2011a).

The ecophysiological and biogeochemical processes model, Biome-BGC (Thornton et al. 2002), has been widely used to simulate forest dynamics in boreal forests, and all physiological input parameters for evergreen needle leaf and deciduous broad leaf forests have been calibrated and validated using field data (White et al. 2000, Bond-Lamberty et al. 2005). An empirical equation is used in Biome-BGC to simulate soil water movement. This description of water flow may be suitable for homogeneous soil profiles; however it is not capable of simulating more complicated soil physics associated with water movement in layered soil profiles. A conceptual system dynamics (SD) model was developed to simulate saturated and unsaturated water movement in multilayered soils. The developed SD model combined both physically-based formulations and empirical assumptions to describe one-dimensional saturated-unsaturated water flow in the vadose zone. The model was successfully calibrated and validated using measured water contents during the infiltration and drainage phases for the studied soils (Huang et al., 2011c). The coupled model, defined as Biome-BGC-CD, has been validated to simulate forest dynamics for jack pine and trembling aspen grown in the layered soils (Huang et al., 2013).

The objective of this study was to evaluate the effect of soil texture (gradation and layering) on plant available water and consequently on forest productivity for reclaimed coarse textured soils in which the sand layers had either well graded or uniform soil textures. The AWHC was used to identify soil moisture regime, while leaf area index (LAI) and net primary production (NPP) as indices of forest productivity.

2. Materials and Methods

2.1. Study area

The study is based on climate and vegetative conditions typical of the oil sands region of northern Alberta, Canada. This area is within the Boreal Mixedwood Ecoregion, with annual total precipitation of 443 mm and mean temperature of 0.7 °C. The soils of interest are coarse textured glacial fluvial and eolian deposits which have generally poor water storage and nutrient properties. The dominant vegetations are jack pine (*Pinusbanksiana Lamb.*), trembling aspen (*PopulustremuloidesMichx.*), and white spruce (*PiceaglauceVoss.*).

Table1. Summary of soil properties for materials

Item	Graded fine sand	Uniform fine sand	Graded coarse sand	Uniform coarse sand
Abb.	GFS	UFS	GCS	UCS
Sand (%)	88.9	99.3	93.0	98.9
Coarse sand (%)	3.3	34.7	75.1	90.0
Medium sand (%)	33.9	24.2	12.7	8.5
Fine sand (%)	51.7	40.4	5.2	0.4
Silt (%)	9.8	0.4	5.2	1.1
Clay (%)	1.3	0.3	1.8	0.0
Bulk density (g cm^{-3})	1.41	1.48	1.45	1.53
Porosity (cm^3 cm^{-3})	0.468	0.442	0.453	0.423
d_{10} (mm)	0.043	0.110	0.154	0.500
d_{60} (mm)	0.298	0.284	0.844	0.788
d_{mean}(mm)	0.234	0.239	0.834	0.826
van Ganutchen parameters				
Θ_s(cm^3 cm^{-3})	0.421	0.398	0.408	0.381
Θ_r(cm^3 cm^{-3})	0.0085	0.0005	0.0070	0.0004
α(1/cm)	0.0510	0.0272	0.1810	0.1158
N	1.766	2.457	2.149	3.587
K_s(cm min^{-1})	0.127	0.642	1.407	10.864

2.2. Materials

Four sands were used in this study, namely graded fine sand (GFS), uniform fine sand (UFS), graded coarse sand (GCS), and uniform coarse sand (UCS) based soil texture and gradation. The particle size analyses were conducted using laser diffraction (Laser Scattering Particle Size Distribution Analyzer Model LA-950, Horiba Instruments Inc., 2008) for 93 particle diameters between 3.0 mm and 1.1e-05 mm, and the results are shown in Fig. 1a. The curve of soil particle size distribution for graded sands is smooth, and sharp for uniform sands.

The particle size distribution (PSD) and soil water retention curve (SWRC) for each soil are shown in Table 1. The four soils have very low clay and silt contents. The UCS is mainly composed of coarse sand particles with a diameter in the range of 0.5 to 2.0 mm, while the UFS mainly consists of fine sand particles with a diameter in the range of 0.06 to 0.25 mm.

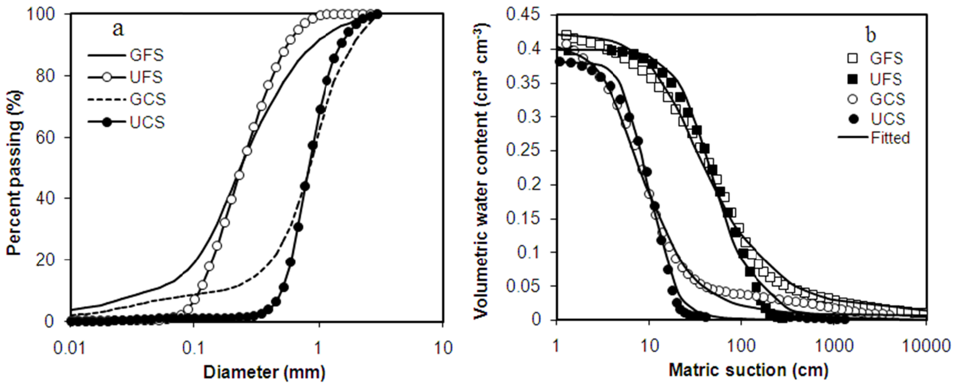

Fig. 1. (a) Particle size distribution for the studied soils; (b) The estimated and fitted soil water retention curves for the studied soils

2.3. Hydraulic properties

In Biome-BGC-SD, the van Genuchten (1980) and Mualem (1976) equations are employed to describe the relationships between water content and suction, and hydraulic conductivity and water content for unsaturated soils, respectively.

Because all materials used in this study are sandy textures, the Arya and Paris pedotransfer function (PTF) (1981) was used to estimate SWRC. Huang et al. (2011b) evaluated the Arya and Paris PTF (1981) using the measured SWRC data for soils taken from the same area, and found that the Arya and Paris PTF (1981) provided an accurate estimate of the SWRC for all sand soils. The estimated and fitted SWRCs for the 4 soils are shown in Fig. 1b, while the fitted parameter values for van Genuchten' equations are shown in Table 1.

The saturated hydraulic conductivity (K_s) for each soil was calculated using the Kozeny-Carman equation. The Kozeny-Carman equation is one of the most widely accepted and used methods for estimating K_s based on grain sizeand its formula is:

$$K_s = D \times \frac{g}{v} \times \left[\frac{\phi^3}{(1-\phi)^2} \right] d_{10}^2 \qquad (1)$$

where g is the gravity (980 cm s^{-2}), v is the kinematic viscosity of water (1×10^{-2} cm^2 s^{-1}), n is the porosity (cm^3 cm^{-3}), d_{10} is the grain diameter at 10% passing (mm), and D is an empirical parameter.The estimated K_s value for each soil was shown in Table 1 based on an empirical parameter of 0.196 for the studied soils optimized by Huang et al. (2011b).

2.4. Soil profiles

A total of 8 different, 1-m soil profiles were simulated. Each profile was assigned a different combination of soil gradation and layering. The 8 soil profiles are: graded fine sand overlying graded coarse sand (GFS/GCS), graded fine sand overlying uniform coarse sand (GFS/UCS), uniform fine sand overlying graded coarse sand (UFS/GCS), uniform fine sand overlying uniform coarse sand (UFS/UCS), graded coarse sand overlying graded fine sand (GCS/GFS), graded coarse sand overlying uniform fine sand (GCS/UFS), uniform coarse sand overlying graded fine sand (UCS/GFS), and uniform coarse sand overlying uniform fine sand (UCS/UFS). The depth of each layer is 50 cm. In addition, 4 homogeneous 1-m profiles of the same sands were used as comparison. All basic properties of soils measured in the fields were assumed unchangeable in this study (Table 1).

2.5. *Simulations of forest LAI and potential productivity*

Maximum LAI and net primary production (NPP) were used as indices of forest potential productivity (Turner et al. 2007). Forest growing dynamics for jack pine and trembling aspen were simulated and the annual maximum LAI and annual NPP were analyzed. The difference in the simulated LAI and NPP for each forest on the layered and homogeneous profiles can be expected to occur due to the effect of soil layering.

The simulations are quite sensitive to initial C and N conditions, which are difficult to estimate since they are strongly affected by long-term disturbance (Thornton et al. 2002). An initialization process, referred to as a spin-up simulation in Biome-BGC, is often used (Turner et al. 2007). In the spin-up simulation, the long-term climatic data was replicated until the C and N balances of the ecosystem reached a state of equilibrium. In our case, a 60-year meteorological series (1944-2007) was collected from Fort McMurray A. station and several thousand iterated simulations were necessary to obtain equilibrium conditions. The same site parameters and physiological parameters were used as input.

The simulation site parameters are obtained from the Fort McMurray A. station, while the soil albedo, nitrogen fixation and deposition were selected to be similar to previous studies in the boreal forest of Alberta (Kimball et al. 1997, Bond-Lamberty et al. 2005). The effective soil depth was determined based on the measured fine root depth; 0.6 m for jack pine and 1 m for trembling aspen (Strong and La Roi 1983). Plant physiological parameters were validated by Huang et al. (2013) using the measured forest dynamical data for jack pine and trembling aspen in the study area.

3. Results and Discussion

3.1. *Available water holding capacity (AWHC)*

There are many methods to determine the FC value for coarse textured soils. The common approach is to measure the water retained in an initially saturated soil profile following at least 2 days of gravity drainage (Hillel 1998). The validated system dynamic model, SD, was used to simulate soil water content profiles following 2 days of gravity drainage from an initially saturated state for each soil. Fig. 2 shows the final water content profiles for all soil profiles.

The capillary barrier affect was created in the four soil profiles with fine sand overlying coarse sand (GFS/GCS, GFS/UCS, UFS/GCS, and UFS/UCS). Compared to the homogeneous profile of GFS, the increased soil water storage in the 0-50 cm profile was 8.9 mm for GFS/GCS, and 14.0 mm for GFS/UCS. This represented an increase of 9.1% for GFS/GCS and 14.4% for GFS/UCS. The maximum suction developed within the GCS or UCS layers is less than that generated within a deep, uniform profile of GFS. This results in a larger volume of water stored in the upper layer as compared to a deep uniform profile of GFS. Compared to the homogeneous profile of UFS, the UFS overlying GCS increased 72.6 mm in the 0-50 cm profile, while the UFS overlying UCS increased by 62.3 mm. This was an increase of 154.2% for UFS/GCS in the 0-50 cm profile and 132.2% for UFS/UCS.

In the case of profiles of coarse sand overlying fine sand (GCS/GFS, UCS/GFS, GCS/UFS, and UCS/UFS) there was always a decrease in soil water storage as compared to the homogeneous GCS or UCS profiles. For example, the GCS overlying UFS decreased 5.3 mm in the 0-50 cm profile as compared to the homogeneous profile of GCS, and 0.5 mm in the 50-100 cm profile as compared to the homogeneous profile of UFS. The GCS/UFS profile stored 80.6 mm less water in the 0-100 cm profile than the UFS/GCS profile. The reason for this was the higher suction that was generated within lower UFS which lowered the water content of the overlying GCS layer below even what might be expected for a deep uniform profile. It is apparent that fine sand underlying coarse sand will actually increase the net percolation from the profile.

The wilting point varies for different plants. Dang et al. (1997) found the wilting point for jack pine was approximately2800 kPa, while Band-Lamberty et al. (2005) testified that a matric suction of 2300 kPa was representative of the wilting pointfor trembling aspen. The water volumes at wilting point varied from 0.3 mm for UCS to 6.1 mm for GFS for jack pine in the root zone of 0-60 cm, and 0.4 mm for UCS to 10.3 mm for GFS for trembling aspen in the root zone of 0-100 cm.

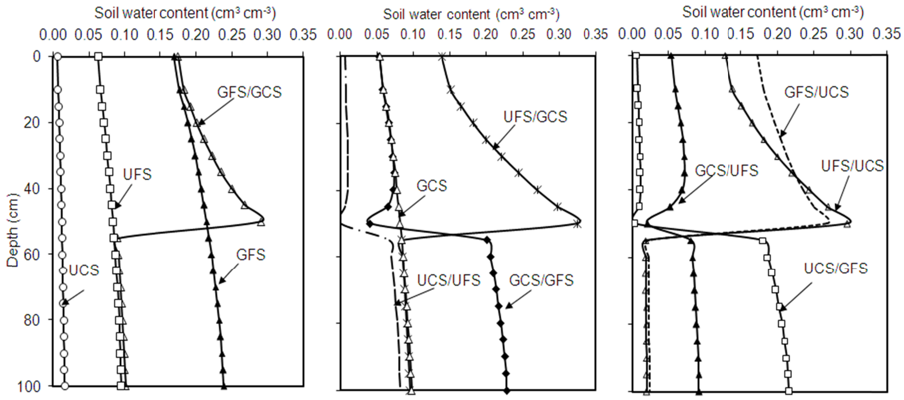

Fig. 2. Soil water content profiles for all columns after 2-day free drainage

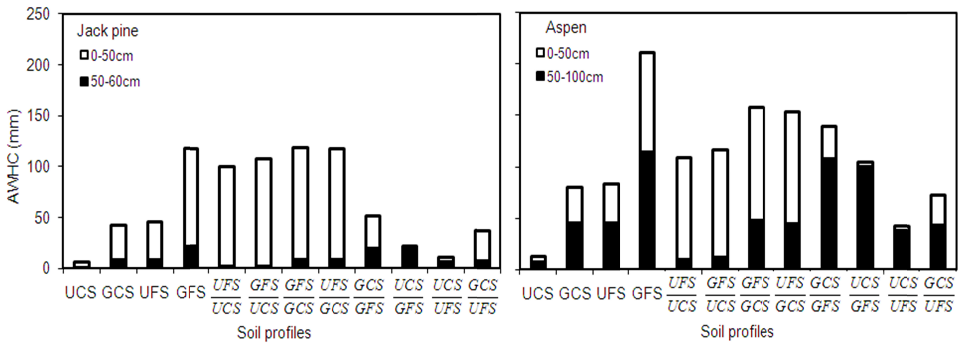

Fig. 3. The available water holding capacity (AWHC) in the root zone for all profiles as a function of soil depth

These water content profiles in Fig. 2 are assumed to represent FC conditions. The AWHC, the difference between FC and wilting point in the root zone, is shown in Fig. 3 for each soil profile for jack pine and aspen. For jack pine, the GFS/GCS had the largest AWHC value of 120 mm among the 12 soil profiles, while the homogeneous UCS had the smallest AWHC value of 6.2 mm. Compared with the homogeneous profile, the layered soil profile with fine sand overlying coarse increased soil water storage in the depth of 0-50cm, whereas the layered soil profile with coarse sand overlying fine sand decreased soil water storage over the same depth. When GFS was the upper soil, the combination of layering and textural gradation did not always improve the AWHC values for jack pine. The AWHC value for GFS/UCS was 108.1 mm, less than the 119.0 mm for the GFS. If the UFS was the upper soil layer, the combination of layering and textural gradation increased the AWHC values for jack pine. The simulated AWHC value was118.1 mm for the UFS/GCS profile, and 101.2 mm for the UFS/UCS profile, and both were much larger than that for the homogeneous UFS (45.7 mm).

The homogeneous GFS had the largest AWHC value for aspen (f211.6 mm), while the homogeneous UCS had the smallest AWHC value (12.3 mm). When GFS was the upper layer of soil did not improve the AWHC values for aspen. The AWHC values for GFS/GCS and GFS/UCS were 158.7 and 117.1 mm, respectively, less than 211.6 mm for the GFS. However, if UFS was the upper soil layer, then the combinations of layering and textural gradation increased the AWHC values for aspen. The simulated AWHC value was 154.2 mm for the UFS/GCS, and 108.8 mm for the UFS/UCS, much larger than that for the homogeneous UFS (82.6 mm).

Therefore, the layer combinations of uniform and textured gradation soils can result in a significant increase in the AWHC values for jack pine and aspen.

3.2. *Response of leaf area index (LAI)*

The LAI from 1948 to 2007 was simulated for jack pine and trembling aspen on the 12 soil profiles. Because LAI changes during the growing seasons, only the annual maximum value was extracted for comparison. Table 2 presents the mean and standard deviation for the maximum LAI for each soil profile. LAI differences for different soil profiles were ascribed to the influence of plant available water. Among the 12 soil profiles, the GFS had the greatest LAI value for aspen and the largest AWHC value (211.6 mm), whereas the UCS had the smallest LAI for aspen and the smallest AWHC value (12.3 mm). A positive but nonlinear relationship between the mean value of the maximum LAI and AWHC was found for each forest type (Fig. 4a).

Forests with larger LAI always consume more water. Soil with a higher AWHC will decrease percolation and hold more water for plant uptake, thus supporting a larger LAI. For example, for the UFS/GCS profile (AWHC of 118.1 mm for jack pine and 154.2 mm for aspen) the mean annual percolation ranged from 55.6 mm (aspen) to 67.8 mm (jack pine), and the maximum LAI ranged from 3.08 (aspen) to 3.14 (jack pine). In the case of the UCS/UFS profile (AWHC value of 10.8 mm for jack pine and 41.9 mm for aspen) the mean annual percolation ranged from 98.5 (aspen) to 239.1 mm (jack pine), and the maximum LAI from 0.78 (jack pine) to 1.76 (aspen).

The enhancement to AWHC produced by the layering of uniform and textural graded soils also results in increases in LAI for each forest. For the UFS/GCS profile, the enhanced AWHC (72.4 mm for jack pine and 71.6 mm for aspen more than the UFS profile) increased the maximum LAI by 1.56 for jack pine, and 0.67 for aspen. For the UFS/UCS prolife, the additional AWHC (55.5 mm for jack pine and 26.2 mm for aspen for than for the UFS profile) increased the maximum LAI by 1.35 for jack pine, and 0.52 for aspen.

The standard deviation values highlight the influence of climate variation on maximum LAI for the two forests. Among all climatic components, drought has the strongest effect on LAI (Alavi 2002). The annual precipitation in this study area ranged from 242 mm in 1998 to 680 mm in 1972 with an average of 443 mm over a 60-year period. In addition, severe low temperatures in winter also restrict LAI (Gholz 1982). Trembling aspen, as a deciduous forest, is more sensitive to climatic variation than jack pine

(Landsberg and Gower 1997) thus the LAI in trembling aspen showed larger inter-annual variation than jack pine.

Table 2. Statistical values of the estimated maximum LAI and NPP for Jack pine and Aspen at each capping

	Maximum LAI		NPP(g C m-2 yr-1)		ET (mm)	
	Mean	STD	Mean	STD	Mean	STD
Jack pine						
UCS	0.67	0.04	122.2	13.4	192.5	23.9
GCS	1.59	0.14	289.5	70.0	317.8	48.2
UFS	1.58	0.14	287.8	73.0	304.0	46.6
GFS	3.18	0.37	792.0	113.8	388.4	74.6
GFS/GCS	3.10	0.87	564.3	233.1	355.0	76.7
GFS/UCS	3.04	0.35	552.5	100.5	353.7	55.1
UFS/GCS	3.14	0.26	572.4	94.9	375.6	60.2
UFS/UCS	2.93	0.26	534.9	97.3	350.1	51.0
GCS/GFS	1.82	0.17	332.0	80.2	329.7	52.2
UCS/GFS	0.84	0.06	152.8	23.2	218.8	28.7
GCS/UFS	1.49	0.14	276.5	50.1	273.3	33.5
UCS/UFS	0.78	0.05	141.8	17.1	204.3	24.9
Aspen						
UCS	0.79	0.07	193.1	25.0	196.9	28.7
GCS	1.92	0.24	468.3	86.2	363.1	52.1
UFS	2.41	0.25	585.9	85.7	369.1	55.7
GFS	3.80	0.46	921.1	141.2	429.0	81.1
GFS/GCS	3.42	0.41	831.4	132.2	417.1	73.7
GFS/UCS	2.95	0.33	717.3	125.0	381.1	63.6
UFS/GCS	3.08	0.37	747.6	124.6	387.8	64.0
UFS/UCS	2.93	0.31	712.0	111.7	377.9	60.5
GCS/GFS	3.05	0.41	740.3	127.6	408.7	69.7
UCS/GFS	2.64	0.35	640.8	110.9	378.6	66.3
GCS/UFS	1.09	0.11	266.2	35.7	230.4	30.6
UCS/UFS	1.76	0.26	425.2	95.6	344.9	53.5

3.3. *Response of forest potential productivity*

The NPP represents forest potential productivity, and the mean and standard deviation values for NPP are shown in Table 2 for all profiles. Compared with the maximum LAI, the NPP appeared to undergo large inter-annual variation for each forest. The NPP differed between the two forest types for the same profile. The NPP for trembling aspen was greater than jack pine. Other scientists have reported that NPP is greater for deciduous than evergreen boreal forests (Gower et al. 1997). The possible reasons for this include greater capacity to absorb light, and greater intrinsic physiological capacity of canopy to convert solar radiation to dry matter (Gower et al. 1997).

The simulated NPP ranged from 122.2 to 580.4 g C m^{-2} yr^{-1} for jack pine, and 193.1 to 921.1 g C m^{-2} yr^{-1} for trembling aspen. These simulated values were in agreement with measurements reported by other researchers in the boreal forest. For example, Hall et al. (1992) and Gower et al. (2001) measured NPP of trembling aspen in Alberta and Saskatchewan ranging from 394 to 500 g C m^{-2} yr^{-1}, and Fassnacht and

Gower (1997) reported NPP from 290 to 470 g C m^{-2} yr^{-1} for jack pine grown in north central Wisconsin. The small differences between the simulated and measured NPP for two forests might result from tree ages, soil water environment, and climatic conditions.

Like LAI, the NPP was nonlinearly correlated to AWHC for each forest (Fig.4b). A similar curvilinear relationship between net canopy assimilation and AWHC was reported by Samposn and Allen (1999) when AWHC varied from 25.0 to 250.0 mm. In this study, the NPP at GFS was about fivefold greater than UCS for two forests.

The optimal combination of uniform fine over texturally graded coarse soil (UFS/GCS) increased the NPP of jack pine by 99%, and the NPP of trembling aspen by 28% (UFS/GCS vs. UFS). The combination of UFS/UCS increased the NPP of jack pine by 86%, and the NPP of trembling aspen by 22%.

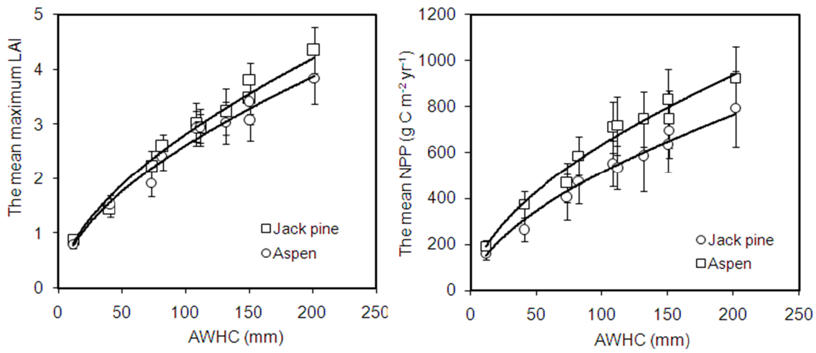

Fig. 4. The relationships between the mean values of (a) the LAI and the AWHC and (b) the NPP and the AWHC for jack pine and aspen

4. Conclusions

In oil sands region of northern Alberta, Canada, it is very important to develop capping transcriptions with coarse sands for increasing plant available water, and consequently assess forest productivity for the reclaimed textured soils using the combination of hydrological and ecological approaches. In this study, a coupled model (Biome-BGC-SD) was used to simulate the available water holding capacity (AWHC) and forest dynamics for jack pine and trembling aspenfor reclaimed coarse textured soils in which the sand layers had either a well graded or uniform soil texture. The simulated results showed that: (1) layered soil profiles with uniform fine sand overlying graded or uniform coarse sand could significantly enhance plant available water; and (2) the maximum values of LAI and potential productivity increased with an increase in plant available water.The results also provided greater insight into the influence of soil texture and layering on plant available water and forest productivity and suggests that incorporating soil layering in reclamation prescriptions should improve reforestation on reclaimed coarse textured soils in the oil sands region (Alberta, Canada).

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